



## Depth Imaging for Unconventional Reservoir Characterization: Canadian Plains Case Study

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### Summary

In seismic imaging, depth migration has replaced time migration in areas with rapid lateral velocity changes such as onshore Canadian foothills and offshore Atlantic Canada and the Gulf of Mexico. In areas with simple flat geology such as the Canadian plains, the value of depth imaging might not be so obvious. In this paper we present results from southeast Saskatchewan showing three main advantages of depth imaging: 1) More quantifiably accurate structural interpretation, 2) Improved focussing and higher resolution, 3) Correct response to azimuthal anisotropy. The first two points help reduce drilling uncertainties and the last point is essential for stress and fracture characterization to better understand unconventional reservoirs.

### Introduction

The data are from the Midale field in southeast Saskatchewan and the regional geological structure is relatively flat; the dominant dip is less than 2°. However, in the zone of interest, azimuthal anisotropy is high and variable in response to changes in stress from CO<sub>2</sub> injection into a naturally fractured reservoir. Pre-stack time and depth migrations were run allowing for a direct apples-to-apples comparison of travel time velocity variation with azimuth analysis (VVAZ) based on time or depth input. Subsequently the time and depth seismic products were also used as inputs to compare the impact of time vs. depth imaging on pre-stack inversion and amplitude versus azimuth (AVAz) analyses. One of the goals of this project was to determine the density and orientation of the natural fractures, and the magnitude and orientation of the principal stresses.

### Processing Method

The 2010 3D field data was pre-processed with an amplitude-preserving flow that contained mild noise attenuation (including 3C surface wave polarization filtering and internal multiple elimination) that was subsequently used as input for both PSTM and PSDM. The initial velocity model for PSDM was built by merging the PSTM velocities (stretched to depth) with a near-surface model obtained from refraction tomography. From there well log data were incorporated to build the anisotropy fields (Thomsen's epsilon and delta), producing a vertical transverse isotropy (VTI) velocity model. This was followed by three iterations of multi-azimuth tomography to update the velocity model and solve for small scale heterogeneities. A global tomography approach was used to update the model, driven by residual moveout on the CIP gathers. Using the final optimally converged tomographic solution, a high-resolution Kirchhoff pre-stack depth migration in common offset vector tile (COVT) domain was performed enabling a detailed comparison of the PSTM and PSDM stacks and gathers.

## Results

An initial obvious advantage of a PSDM image over a PSTM image is the fact that the PSDM image is a quantifiably accurate structural representation of the subsurface. The depth accuracy was validated by comparing depths of well top markers with horizons picked on the PSDM stack section. It was found that about 95% of well tops near the zone of interest had well miss-tie errors below 1%.

While it is possible (and routinely applied) to stretch the PSTM stack to one-way-depth, the results suffer from several drawbacks. Firstly, the PSTM migration velocities are derived to provide the best CIP gather focussing and this does not guarantee depth accuracy. To improve the depth accuracy, one can make use of well top to refine the stretching velocities. However this does not remove depth uncertainties in regions far from and between the wells. In Figure 1, it is obvious that the time-to-depth stretching has introduced false structures to the section on the left (the red line is to help guide the eye). The undulations on the stretched PSTM stacks are depth inaccuracies and can be up to 50m in magnitude.

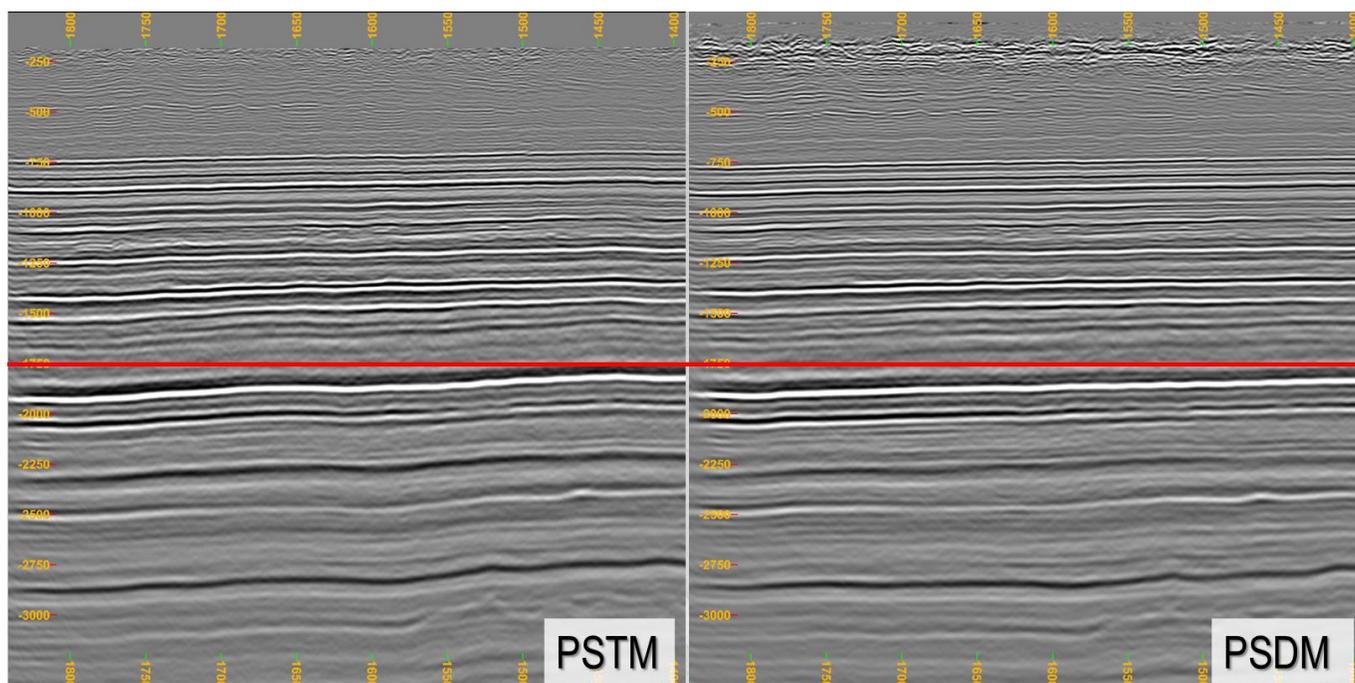


Figure 1: PSTM stretched to one-way-depth (left) and PSDM of the same inline. Note the false structures introduced by PSTM stretching (the horizontal red line helps guide the eye).

Beyond the above quantitative advantage, the image from PSDM is noticeably superior, especially in the shallow section. In Figure 2, we see the PSDM is better focussed and has higher SNR. As a result, it is easier to delineate the horst and graben structures, and the better resolved continuity of steep faults. In these areas, the PSDM CIP depth gathers display flatter events and less jitter in the residual moveout.

The main reason for this difference in image quality is due to the velocity heterogeneities just below the topographical surface in the final VTI model, possibly caused by erosion and weathering. Time migration does not honor these small variations even when they are included in the velocity model since time migration assumes a laterally invariant velocity profile for each common image point (CIP). Further significant velocity heterogeneities are evident around 600m to 800m below the elevation surface.

The simple flat geology of Canadian plains data could mislead one into thinking that the velocity model is also layer cake. In this survey, there are intervals in which that assumption does not hold and this departure impairs the time-migrated gathers and stack.

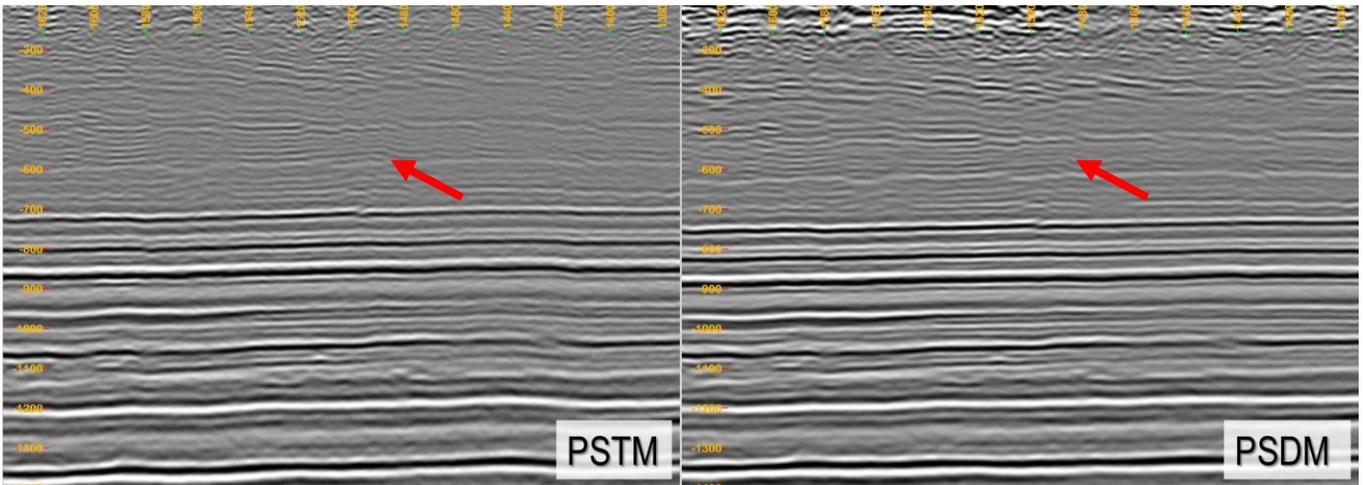


Figure 2: Zoomed-in view of the shallow section. Note the PSDM section on the right is cleaner and more resolved with the steep faults being better imaged.

The third advantage of depth migration is its correct (transmission travel time compensated) response to azimuthal anisotropy as can be seen on Common Offset Common Azimuth (COCA) gathers. In areas with high azimuthal anisotropy, variations in residual moveout are correlated with azimuth, an effect commonly known as velocity versus azimuth (VVAz). In some locations the VVAz effect is present in both the PSTM and PSDM gathers but there were many instances there is a significant difference in the magnitude of VVAz, as indicated by the red arrows in Figure 3.

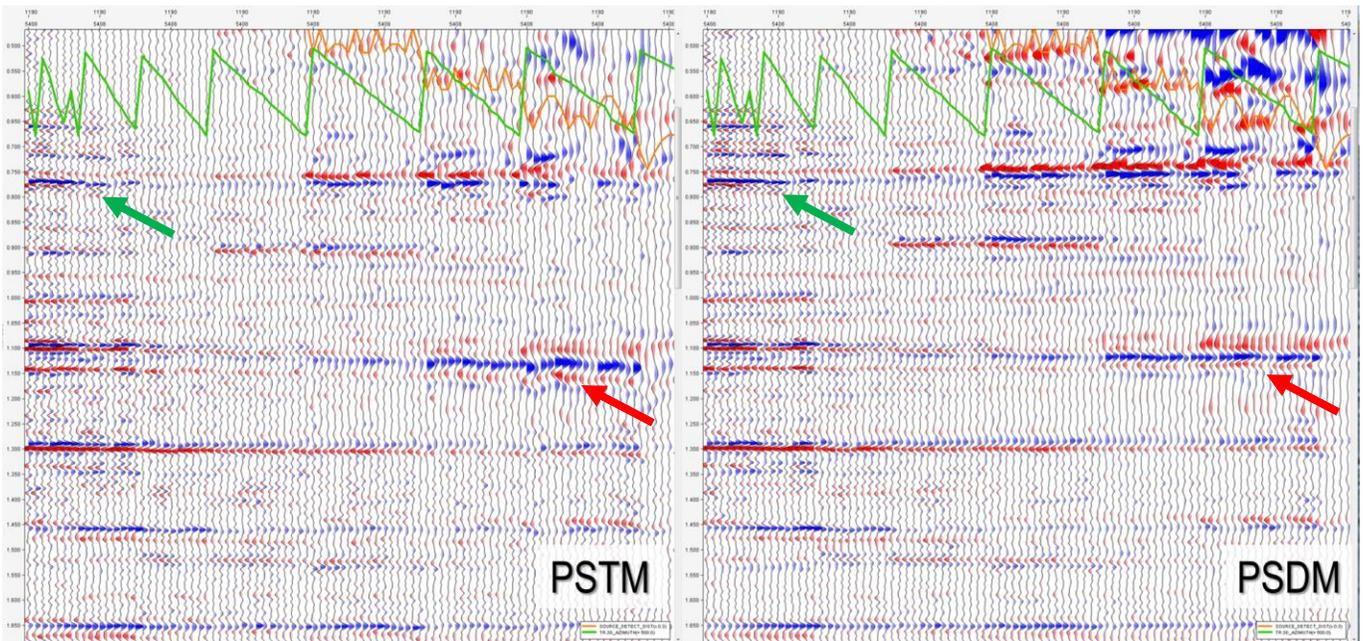


Figure 3: PSTM and PSDM gathers on the same CIP location. The VVAz effect can be seen on the PSTM gather but is barely present on the PSDM gather (red arrows). Also note the sharper better resolved wavelets near the red arrows.

The source of this discrepancy can be traced to the limitation of time migration. Small scale velocity heterogeneities in the overburden that varies with azimuth can also lead to VVAz effect on deeper events on time-migrated gathers. However somewhat surprisingly, the VVAz effect on a target event can be due

to any combination of overburden heterogeneities and target zone azimuthal anisotropy. In general, there is no way to disentangle these two contributions on PSTM gathers.

Depth imaging overcomes this confusion or distortion by first tomographically solving for these heterogeneities and then honoring them in depth migration. The fact that gathers are flatter on PSDM gathers in the shallow, as indicated by the green arrows in Figure 3, bears out this claim. This is also confirmed by comparing the PSDM gathers of the initial and the final velocity model. The events in the shallow are noticeably flatter and the VVAz effect is significantly attenuated after three rounds of tomography.

Next, a full volume VVAz anisotropy analysis was performed on both PSTM and PSDM gathers at the zone of interest. While they do agree in some areas, there are large regions where the PSDM results show hardly any anisotropy while the PSTM results show anisotropy of up to 4%, see Figure 4. In summary, depth imaging can minimize these flawed false positive VVAz effects and as a result the VVAz signal is more strongly correlated to a realistic azimuthal anisotropy.

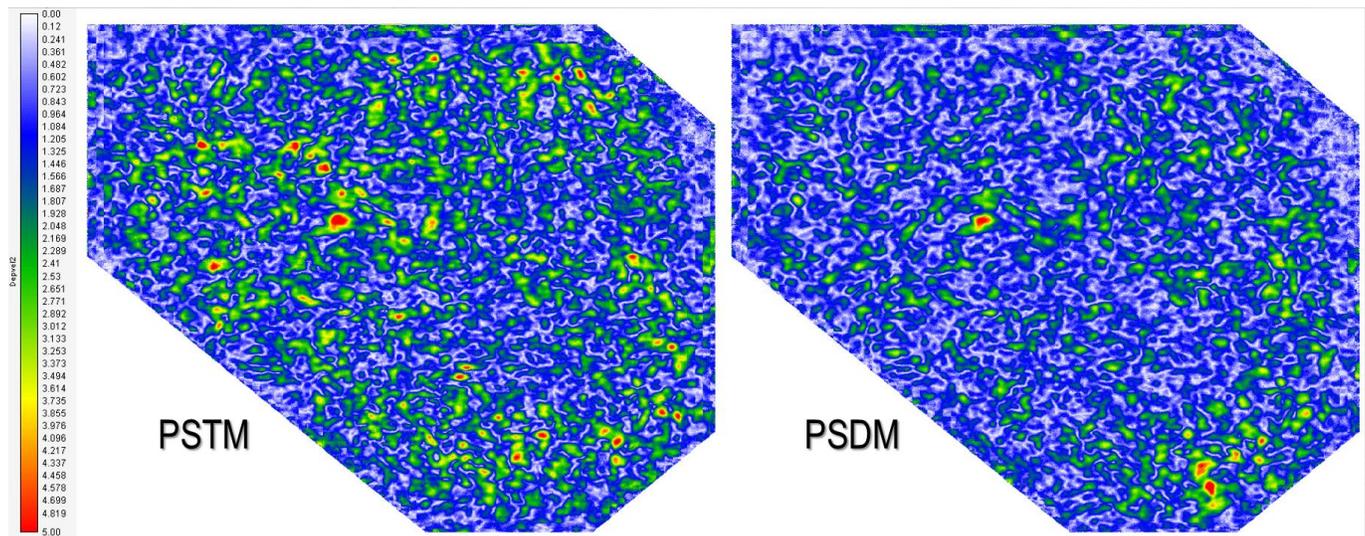


Figure 4: Azimuthal anisotropy percentage values (range is from 0% to 5%) extracted from PSTM gathers (left) and PSDM gathers (right) at the zone of interest.

## Conclusions

We have shown that depth imaging has three distinct advantages even when the geology is very simple and structures are flat. Firstly, the seismic cube in depth is an accurate earth representation that can help reduce drilling risks, especially for horizontal drilling and geo-steering. Secondly, depth migration provides a better focussed image and shows more detail where the velocities deviate from being laterally invariant, the core assumption of time migration. The data here shows these deviations do occur even when the geology is layer cake in appearance. Finally, depth migration minimizes spurious VVAz signal at the zone of interest by accurately modelling velocity heterogeneities in the overburden. This is crucial when the VVAz response is used to characterize the azimuthal anisotropy of unconventional reservoirs.

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